Journal of Arid Environments 165 (2019) 106–118

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Spatiotemporal variations and its influencing factors of grassland net primary productivity in Inner Mongolia, China during the period 2000–2014

Yuling Zhao[a,b,c], Haixin Liu[b,c,d,*], Anbing Zhang[b,c], Ximin Cui[a], Anzhou Zhao[b,c]

[a] College of Geoscience and Surveying Engineering, China University of Mining & Technology Beijing, Beijing, 100083, China
[b] School of Mining and Geomatics, Hebei University of Engineering, Handan, Hebei Province, 056038, China
[c] Collaborative Innovation Center of Comprehensive Development and Utilization of Coal Resource of Hebei Province, Handan, Hebei Province, 056038, China
[d] College of Geomatics, Shandong University of Science and Technology, 579 Qianwangang Road Economic & Technical Development Zone, Qingdao, Shandong Province, 266510, China

ARTICLE INFO

Keywords:
MOD17-A3
Net primary productivity
Climate change
Anthropogenic activities
Growing season average land surface temperature

ABSTRACT

The quantification of changes in long-term trends in grassland net primary productivity (NPP) and its large-scale driving forces are important for understanding terrestrial ecosystem changes in arid and semi-arid regions. Based on the MODIS-NPP dataset, this study investigated patterns in the spatiotemporal variations in NPP and its possible influencing factors in Inner Mongolia during 2000–2014 using the linear trend analysis method, correlation analysis, and an *F* test. The results show that grassland NPP had an annual rate of increase of 4.53 g C/(m^2·a) with a significant increasing trend ($p < 0.01$). Spatial analysis results indicate that the average grassland NPP presented a gradual increasing trend from southwest to northeast, with an area of longitudinal zonality being identified. Grassland NPP presented a significant increase ($p < 0.05$) in more than 31.93% of the region. Grassland NPP and growing season precipitation (GSP) had a significant negative correlation in 54.78% of the study area. Grassland NPP and the growing season average land surface temperature (GSALST) had a significant negative correlation for 65.93% of the study area; growing season average temperature (GSAT) had no significant effect on the grassland NPP. For different grassland types, GSP had the greatest impact on alpine meadows ($r = 0.73$), and GSALST had the greatest impact on alpine steppes and alpine meadows ($r = -0.81$). Related ecological restoration projects such as fenced rangeland and planted grass played a positive impact on annual NPP in the study area.

1. Introduction

As an important part of terrestrial ecosystems, grasslands account for about 1/3 of the global land surface area (Mowll et al., 2015). They provide important ecosystem service functions, such as forage production and vital habitats, for many organisms (Lal, 2004). The Inner Mongolian grasslands are an important component of the International Geosphere-Biosphere Programme temperate forest-steppe transect in Northeast China; it is also an important animal husbandry production base in China. Human activities are intense here, and, with arid and semi-arid regions comprising most of the area, the ecological environment is extremely fragile (Sun and Wang, 2008; Zhang et al., 2016). Given that many grassland ecosystem services depend on their productivity, it is important to quantitatively analyze the spatiotemporal variations in the characteristics of grassland net primary productivity (NPP) and its associated response to relevant influencing factors to better utilize grassland resources and improve the sustainable development of the ecosystem.

NPP refers to the remaining amount of dry organic matter generated through photosynthesis after deducting autotrophic respiration; this includes the production generated by plant branches, leaves, roots, and plant litter (Field et al., 1995). As a critical variable characterizing vegetation productivity, NPP constitutes not only the basis of organism energy and material cycles, but also the basis of ecosystem energy and material flow. It influences the strength of ecosystems in terms of carbon fixation capacity (Haberl et al., 2007; Imhoff et al., 2004; Steffen et al., 1998). The development of remote sensing technology has led to its wide usage in NPP estimation models at regional and global scales (Cramer et al., 1999; Zhu et al., 2005). Since the mid-19th century, scholars worldwide have been studying the relationship between global or regional grassland NPP and climatic factors, especially temperature and precipitation (Li et al., 2015; Zhang et al., 2016).

* Corresponding author. School of Mining and Geomatics, Hebei University of Engineering, Handan, Hebei Province, 056038, China.
E-mail addresses: zhaoyuling@hebeu.edu.cn (Y. Zhao), gislhx@hebeu.edu.cn (H. Liu), zhanganbing@hebeu.edu.cn (A. Zhang), cxm@cumtb.edu.cn (X. Cui), zhaoanzhou@126.com (A. Zhao).

https://doi.org/10.1016/j.jaridenv.2019.01.004
Received 12 June 2018; Received in revised form 21 October 2018; Accepted 9 January 2019
Available online 04 February 2019
0140-1963/ © 2019 Elsevier Ltd. All rights reserved.

However, the response of grassland NPP to climate variability at global scales has shown relatively significant spatiotemporal heterogeneity, and different grassland types have different levels of sensitivity to climate change. Therefore, the driving mechanism of grassland NPP spatiotemporal variability at regional scales is not completely clear (Cramer et al., 1999). At present, some scholars have carried out a series of studies on vegetation NPP or grassland NPP in Inner Mongolia (Zhu et al., 2005; Han et al., 2015; Yuan et al., 2015; Lin and Dugarsuren, 2015) and achieved good results. However, there are different opinions on the response of grassland NPP to climatic factors in Inner Mongolia. Some studies believe that precipitation has a greater impact than does temperature (Long et al., 2010), while others believe that there are different responses to precipitation and temperature for the NPP of different grassland types (Mu et al., 2013). At present, some papers have analyzed the temporal and spatial evolution of NPP and its driving factors in this area. However, the analyses focused on the impact of climate factors such as precipitation and temperature, ignoring the impacts of related ecological restoration projects such as fenced rangeland and planted grass.

Therefore, in this paper, the MODIS/Terra MOD17A3-NPP and MOD11-LST datasets, as well as growing season precipitation (GSP), growing season average temperature (GSAT), and growing season average land surface temperature (GSALST) are adopted to determine the following: 1) the spatial patterns and spatiotemporal variations in grassland NPP in Inner Mongolia from 2000 to 2014; 2) the response mechanisms of grassland NPP in the study area to GSP, GSAT, and GSALST; 3) the impacts of human activities related to ecological protection and restoration policies on grassland NPP in the study area.

2. Data and methods

2.1. Overview of the study area

The Inner Mongolia Autonomous Region (~37°24′–53°23′N, ~97°12′–126°04′E) is located in China's northern border region and on the Inner Mongolian Plateau, with a total area of about 1,180,000 km^2. The study area, dominated by the Inner Mongolia Plateau, has an average altitude of 1000–1200 m. It consists of flat terrain with the Greater Khingan Mountains to the east and the Yinshan and Helan Mountains to the south. The climate of the steppe area is a typical temperate continental climate with an annual precipitation of 50–450 mm and an annual average temperature of −1 °C to 10 °C, experiencing a gradual transition from humid and semi-humid areas in the east to semi-arid and arid areas in the west. The precipitation gradually decreases from northeast to southwest, while the temperature gradually increases from northeast to southwest. The long and narrow area as a whole extends from the northeast to the southwest and constitutes a main distribution area of temperate steppes in China. Grassland in the study area accounts for about 67% of the total area of Inner Mongolia and 22% of the total grassland area in China. The main grassland types there are shown in Fig. 1.

2.2. Data sources and data processing

2.2.1. Net primary productivity data

The NPP data adopted in this paper were derived from the 2000–2014 MOD17A3-NPP dataset of NASA EOS/MODIS. The MOD17A3 NPP products were acquired on the basis of the MODIS sensor on the Terra satellite. These include the global precise terrestrial vegetation NPP inter-annual variation data products calculated by the MODIS terrestrial research group with the Biome-BGC (biome-biogeochemical cycles) model (Foley, 1994) with a spatial resolution of 500 m. The dataset has been widely used in research on global and regional NPP and carbon cycles (Zhao et al., 2005; Xia et al., 2015; M. Zhang et al., 2017a,b).

2.2.2. Land surface temperature data

The land surface temperature (LST) data adopted in this paper were provided by the Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn) with a spatial resolution of 1 km. The product was synthesized by the MODLT1T product, and the calculation method utilized the average monthly value. To ensure its consistency with the NPP data and facilitate the subsequent correlation analysis, the product data selected in this paper range from April to October in 2000–2014 (which is the growing season of vegetation), and the average values from April to October were calculated as the growing season LSTs. Meanwhile, the cubic convolution re-sampling method was adopted to adjust the resolution to 500 m.

2.2.3. Meteorological data

The meteorological data were extracted from the China Meteorological Data Service Center (http://data.cma.cn), which included the observation data of 47 land surface meteorological stations distributed throughout Inner Mongolia (Fig. 1) from 2000 to 2014. The data include latitude and longitude information as well as the GSAT and GSP of each meteorological station. According to the latitude and longitude information, the Geostatistical Analyst module of ArcGIS was adopted to perform inverse distance spatial interpolation for the meteorological data, so as to obtain the meteorological data raster image with consistent pixel sizes and identical projections as the NPP data. The raster images of GSAT and GSP in the study area were cropped using a data mask.

2.2.4. Grassland type data

The grassland type map of the Inner Mongolian Autonomous Region in 2010 was provided by the Inner Mongolian Institute of Grassland Surveying and Planning (Xie et al., 2018). The grassland type classification system was adopted by combining the botanical point of view and the classifiable characteristics of Landsat images for grassland vegetation (Sha et al., 2009; Li et al., 2013).

2.3. Study methods

2.3.1. Linear trend analysis method

Unitary linear regression analysis, which is widely used in long-term sequence dynamic monitoring of vegetation variation, can simulate the change trend of each raster. The time-variation characteristics of a single pixel reflect all of the spatial variations, comprehensively reflecting the evolution of regional spatiotemporal patterns (Zhao et al., 2017). The slope in a single pixel of the multiyear regression equation is the inter-annual change rate. A positive slope value means that NPP has increased with time; as the regional vegetation productivity tends to increase, the greater the value, the more evident the increasing trend will be. Conversely, a negative slope value means that NPP tends to decrease with time. The equation is:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times NPP_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NPP_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}, \quad (1)$$

where θ_{slope} is the trend slope; n is the number of years in the monitoring period; and NPP_i is the vegetation NPP of the ith year. The trend significance test adopts the F test, where significance only represents the confidence level of a trend change and has nothing to do with the speed of change. The equation for the statistical magnitude is:

$$F = U \times \frac{n-2}{Q}, \quad (2)$$

$$U = \sum_{i=1}^{n} (\widehat{y_i} - \overline{y})^2, \quad (3)$$

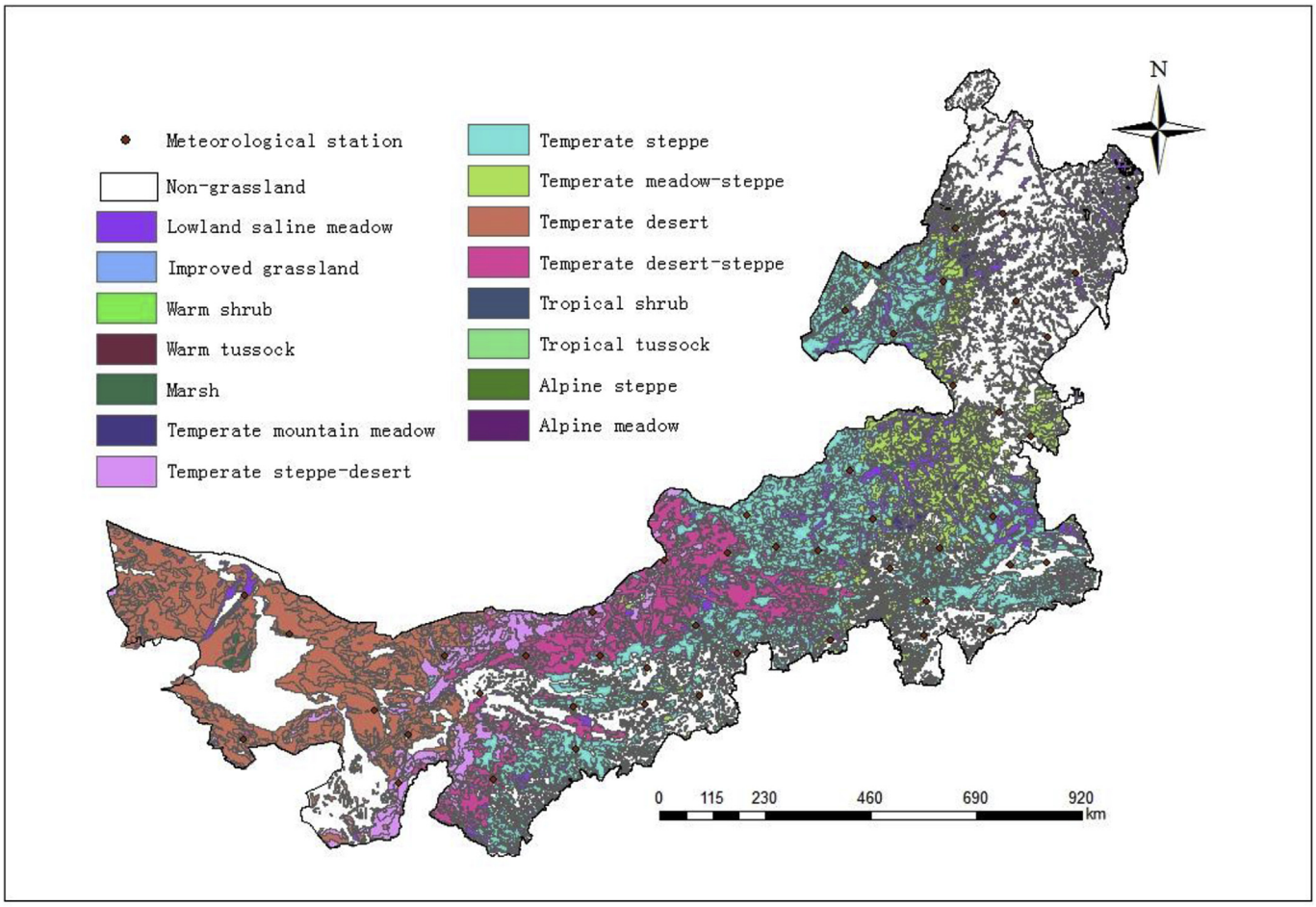


Fig. 1. Grassland types and meteorological station distributions in the study area.

$$Q = \sum_{i=1}^{n} (y_i - \widehat{y_i})^2, \tag{4}$$

Equation (3) and Equation (4) are respectively called the error sum of squares and the regression sum of squares, y_i is the actual observed NPP value of the ith year; $\widehat{y_i}$ is the regression value; $\overline{y}$ is the average NPP value of the 15 years; and n is the number of observation years (n = 15 in this study). According to the test results, the change trend is divided into five grades: extremely significant decrease ($\theta_{slope} < 0$, $p < 0.01$), significant decrease ($\theta_{slope} < 0$, $0.01 < p < 0.05$), insignificant change ($p > 0.05$), significant increase ($\theta_{slope} > 0$, $0.01 < p < 0.05$), and extremely significant increase ($\theta_{slope} > 0$, $p < 0.01$).

2.3.2. Correlation analysis between NPP and meteorological factors

The pixel-based spatial analysis method was adopted to analyze the responses of NPP to GSAT, GSP, and GSALST. The simple correlation coefficient is calculated first (Equation (5)), and then the partial correlation coefficient between NPP and GSAT/GSP is determined (Equation (6)). When two variables are correlated with a third variable at the same time, the correlation coefficient between the two variables after eliminating the influence of the third variable is referred to as a partial correlation coefficient, which can better reflect the impact of a single factor on NPP. Therefore, the partial correlation coefficient is adopted in this paper to study both the NPP-GSAT correlation and the NPP-GSP correlation:

$$R_{xy} = \frac{\sum_{i=1}^{n} [(x_i - \overline{x})(y_i - \overline{y})]}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 \sum_{i=1}^{n} (y_i - \overline{y})^2}}, \tag{5}$$

$$r_{12,3} = \frac{r_{12} - r_{13} r_{23}}{\sqrt{(1 - r_{13}^2) + (1 - r_{23}^2)}}, \tag{6}$$

where $r_{12,3}$ is the partial correlation coefficient between variable 1 and variable 2 after fixing variable 3; r_{12}, r_{13}, and r_{23} respectively represent the partial correlation coefficients between variable 1 and variable 2, variable 1 and variable 3, and variable 2 and variable 3.

3. Results and analysis

3.1. Spatial patterns of NPP in the study area

The spatial distribution of the average grassland NPP in the study area during the period of 2000–2014 is shown in Fig. 2. It can be seen that the average grassland NPP gradually increased from west to east and from south to north during the study period. The NPP values to the west of Xilin Gol League were mostly below 200 g C/(m^2·a), while the NPP values in the western and central regions of Hulun Buir and the junction regions of Xilin Gol League, with Hinggan League, Tongliao, and Chifeng, were basically above 300 g C/(m^2·a). Combined with the distribution map of grassland types in Inner Mongolia (Fig. 1), it can be seen that high NPP values were mainly distributed in low-temperature and high-precipitation meadow regions, while low NPP values were mainly in high-temperature and low-precipitation steppe regions. Given the longitudinal variation law (Fig. 3), the distribution of the average annual grassland NPP in Inner Mongolia showed an evident longitudinal zonality, with a gradual increase from west to east and a variation rate of 263 g C/(m^2·a·10°) ($p < 0.01$). NPPs in different types of grassland also differed greatly (Table 1), with a variation interval of

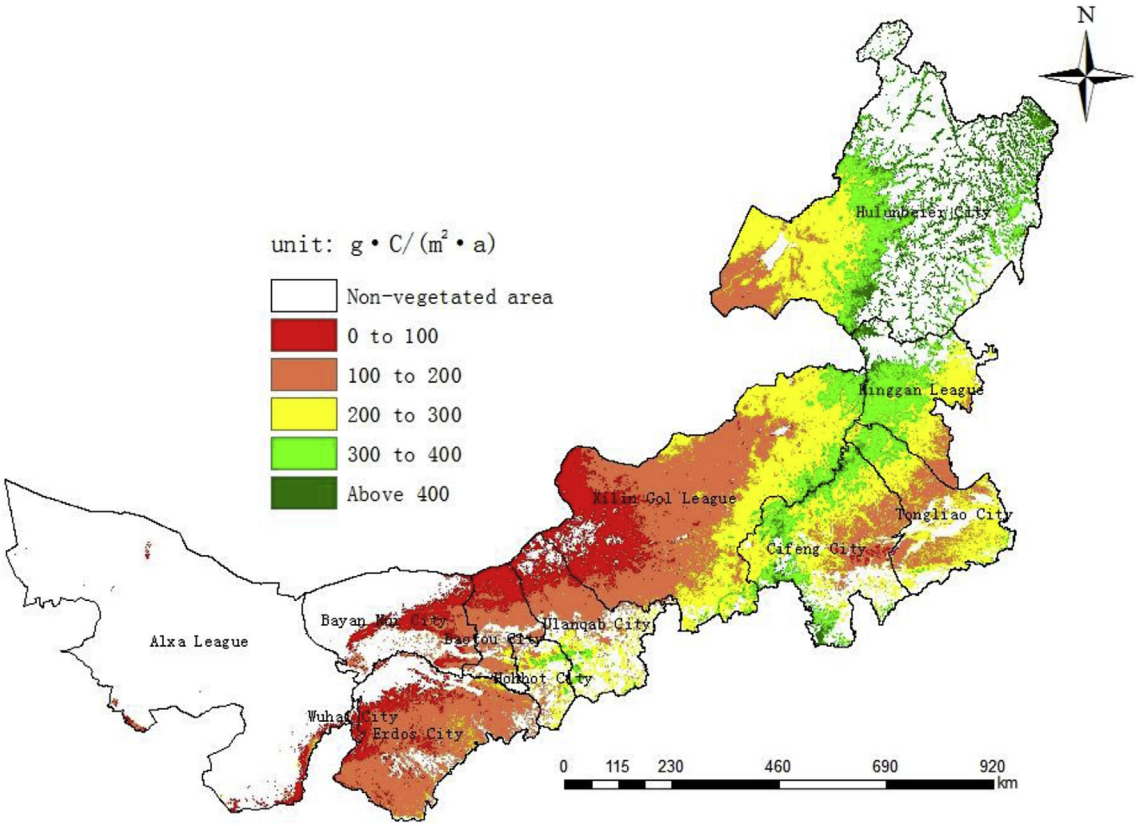


Fig. 2. Spatial distribution map of the average grassland NPP in the study area, 2000–2014.

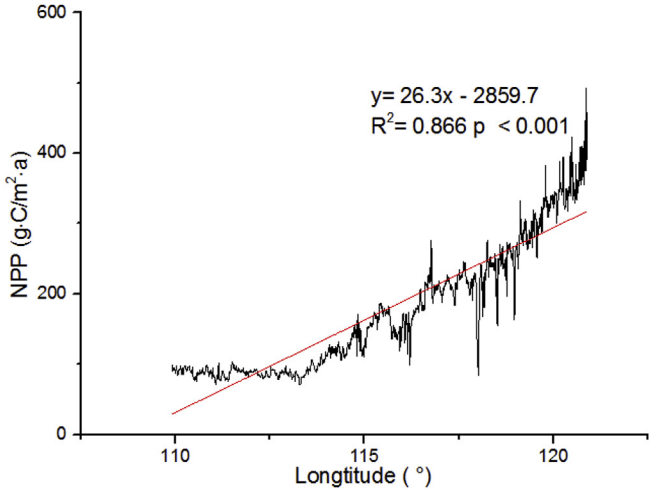


Fig. 3. Longitudinal variation law of the average grassland NPP in the study area, 2000–2014.

81.21 g C/(m^2·a) to 365.53 g C/(m^2·a).

A comparison of the spatial distribution of grassland NPP (Fig. 4) shows that the NPP in the study area varied significantly. At the beginning of the study period (Fig. 4a; 2000), the NPP gradually decreased from northeast to southwest, and the regions with an annual NPP greater than 200 g C/(m^2·a) were mainly in the northeast, accounting for a small portion of the study area. Over time, however, regions with an annual NPP greater than 200 g C/(m^2·a) gradually advanced towards the southwest; thus, by the end of the study period (Fig. 4b; 2014), regions with an annual NPP less than 100 g C/(m^2·a) were mainly located in the west of Xilin Gol League, the north of Baotou and Ulanqab, and the regions at junctions with the desert.

Table 1
Average NPP of various grassland types during 2000–2014.

Grassland type	Average NPP (g·C/(m^2·a))
Lowland saline meadow	291.40
Improved grassland	181.45
Alpine meadow	180.11
Alpine steppe	81.21
Warm tussock	172.76
Warm shrub	313.75
Tropical tussock	180.74
Tropical shrub	257.30
Temperate meadow-steppe	301.56
Temperate steppe-desert	98.45
Temperate steppe	192.11
Temperate desert-steppe	111.99
Temperate desert	108.38
Temperate mountain meadow	365.53
Marsh	286.74

Equation (1) was used to calculate the variation rate in the grassland NPP by pixel, and Equation (2) was used to conduct *F* significance tests on the variation trends (Fig. 5). The results clearly show that the grassland NPP had an extremely significant (significant) increase in 13.36% (18.57%) of the study area, mainly in the south of Erdos, the north of Xilin Gol League, Hinggan League, and the vast majority of grassland regions in Hulun Buir. Regions with significant decreases and extremely significant decreases only accounted for about 0.44% of the study area. Statistical analysis in combination with the grassland type map of the study area (Fig. 1) showed that the vegetation NPP values of temperate steppes had a trend of extremely significant increase; the NPP of temperate meadow-steppes and temperate desert-steppes had a relatively significant increase.

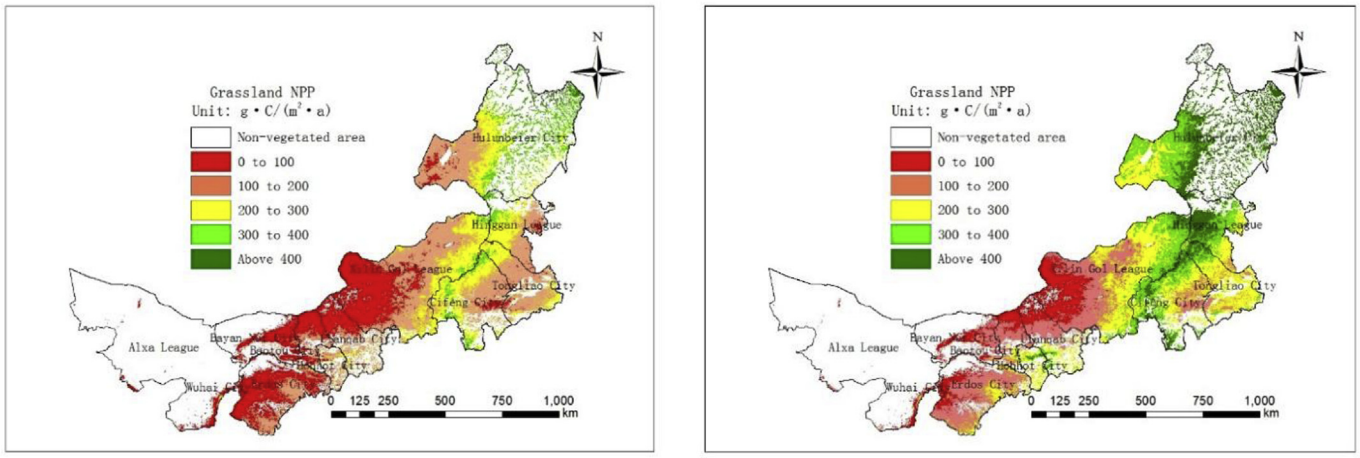


Fig. 4. Spatial distribution of the grassland NPP in the study area in (a) 2000 and (b) 2014.

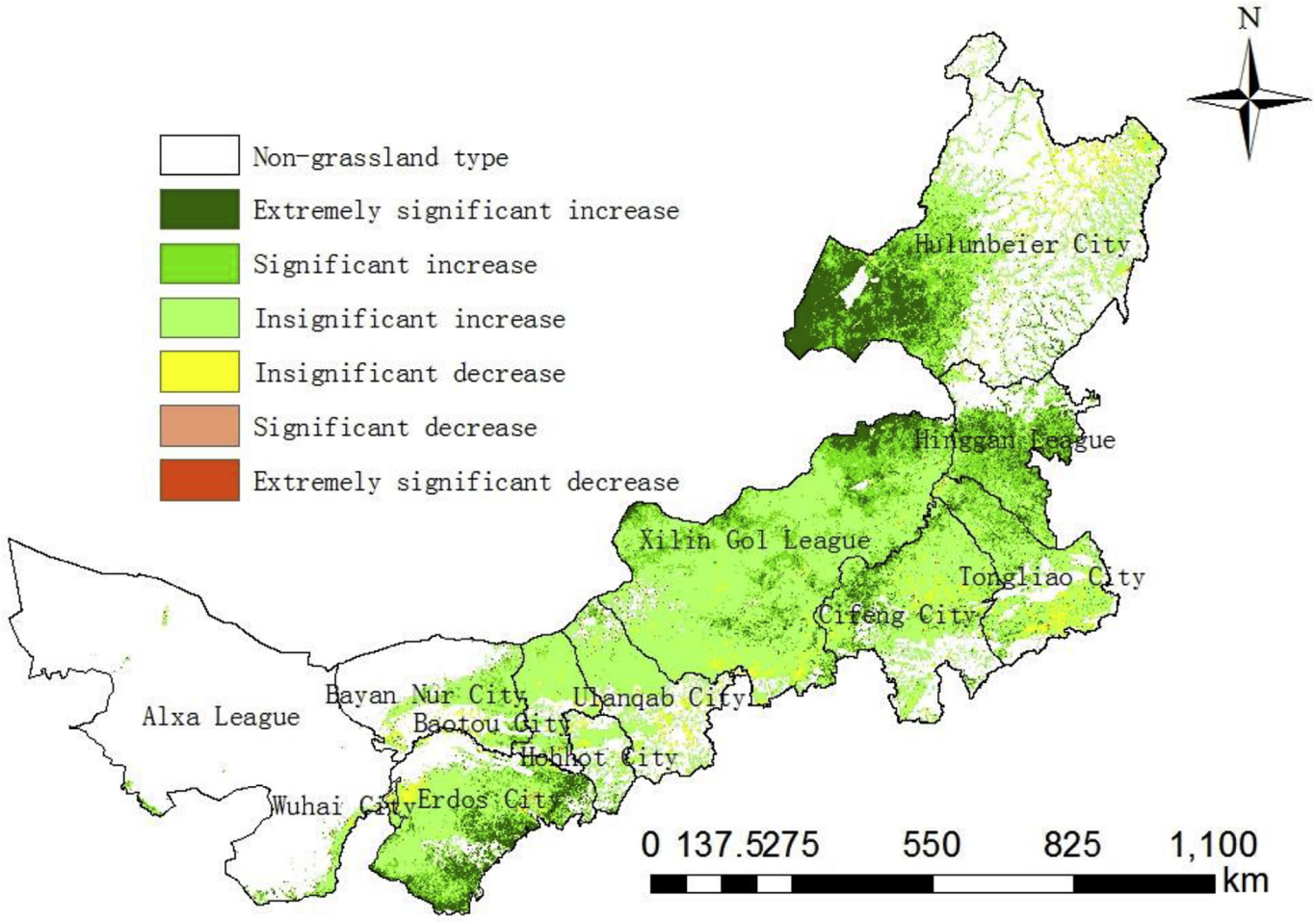


Fig. 5. Variation significance of grassland NPP in the study area, 2000–2014.

3.2. Inter-annual variations in NPP in the study area

From 2000 to 2014, the grassland NPP in the study area showed a trend of wavelike increase (Fig. 6), with an annual increase rate of 4.53 g C/(m^2·a). The minimum value, which was 22.91% lower than the average value of the study period, was recorded in 2001, which is consistent with the research results obtained by Mu et al. (2013). The overall grassland NPP in the study area gradually increased from 6.91×10^5 kg C/a in 2000 to 9.03×10^5 kg C/a in 2014, suggesting that the carbon sequestration capacity of the study area was enhanced year by year. In addition, the proportion of regions with a grassland NPP less than 100 g C/(m^2·a) gradually declined from over 22.3% in

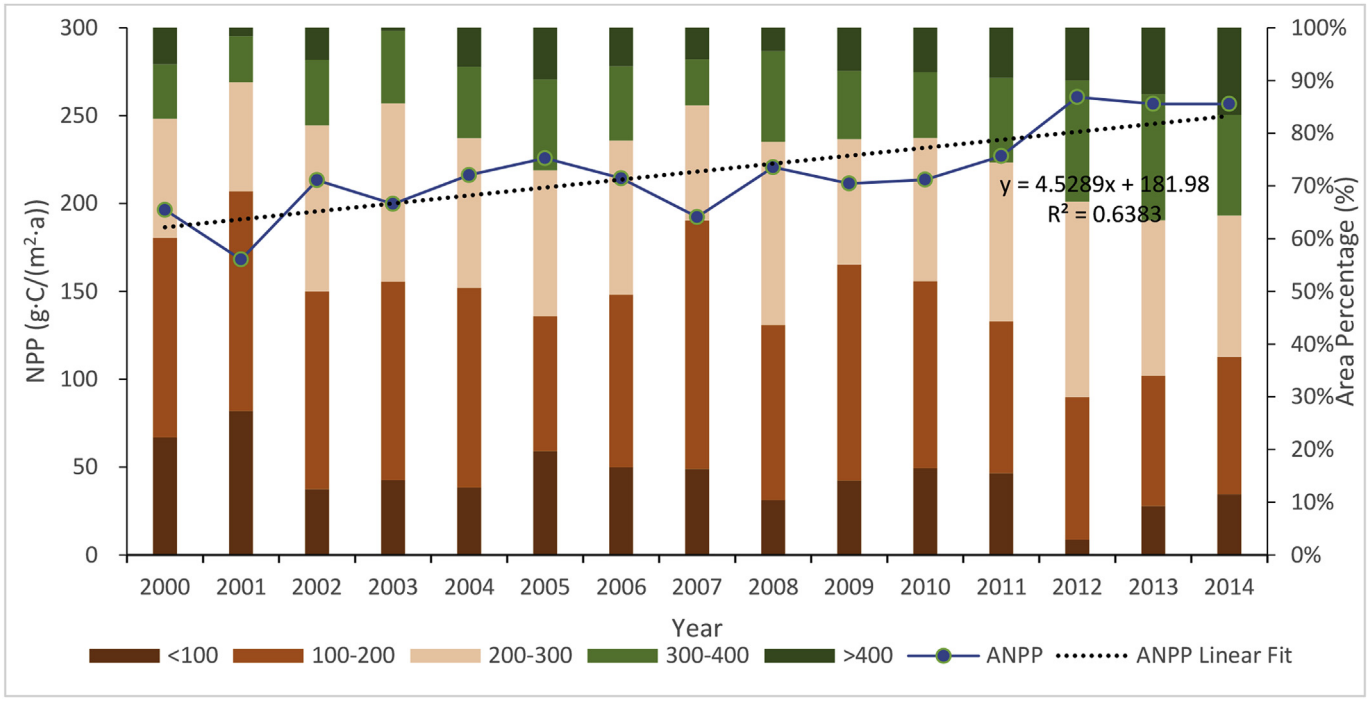


Fig. 6. Inter-annual variation in the NPP of the study area, 2000–2014.

2000 to 11.5% in 2014, and regions with an annual average NPP of more than 300 g C/(m^2·a) increased from 17.2% in 2000 to 35.6% in 2014. These results indicate that grassland NPP in the study area was increasing steadily.

To further analyze the inter-annual variations in various grassland types, we further evaluated the six most dominant grassland types: lowland saline meadow, temperate meadow-steppe, temperate steppe-desert, temperate steppe, temperate desert-steppe, and temperate desert. These types cover 98.14% of the study area. Their variation trends over time are shown in Fig. 7, and their statistical data are shown in Table 2. It can be seen that the six dominant grassland types have variation trends similar to the overall NPP of the study area, both showing a wavelike increase. The variation in NPP can be classified into three levels: temperate meadow-steppes and lowland saline meadows belong to the first level, with relatively high average NPP values; temperate steppes belong to the second level, with a moderately average NPP value; and temperate steppe-deserts, temperate desert-steppes, and temperate deserts belong to the third level, with the lowest average NPP values (Fig. 7). It can be seen from Table 2 that the temperate meadow-steppes had the highest increase rate of 6.67 g C/(m^2·a); both the first and the second levels had increase rates of over 4.5 g C/(m^2·a). The third level had an increase rate of less than 2.5 g C/(m^2·a), with the lowest increase rate of 1.57 g C/(m^2·a) in temperate steppe-deserts. The variation trends of the six grassland types were all significant ($p < 0.05$).

3.3. Influence of climatic factors on grassland NPP

Analysis of the GSAT data from the 47 meteorological stations in the study area showed a decline rate of −0.01 °C/a from 2000 to 2014

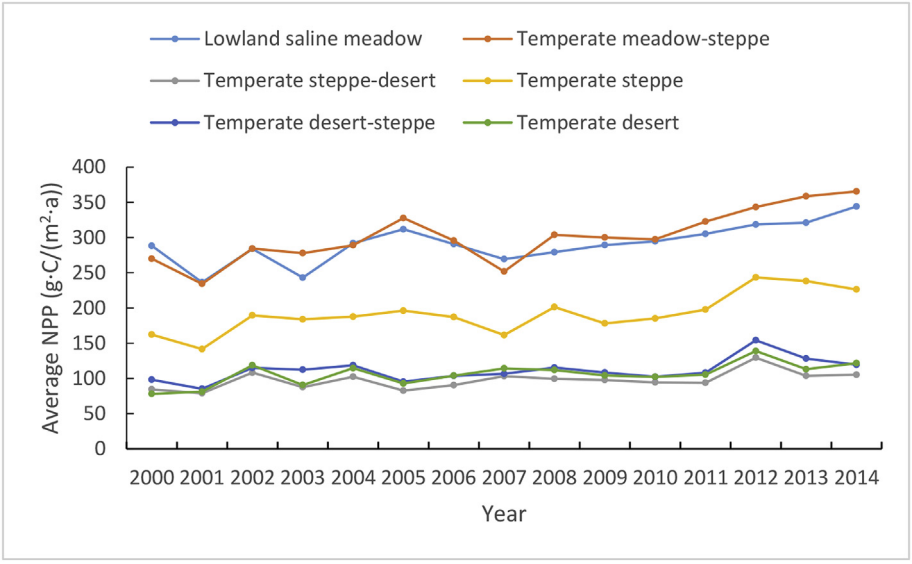


Fig. 7. Inter-annual variations in NPP for the six main grassland types.

Table 2
NPP inter-annual variation trend statistics of dominant grassland types.

Grassland type	Trend line	Determination coefficient R^2	Significance
Lowland saline meadow	y = 4.54x - 8826.16	0.48442	$p < 0.01$
Temperate meadow-steppe	y = 6.67x - 13087.09	0.6185	$p < 0.01$
Temperate steppe-desert	y = 1.57x - 3061.70	0.26152	$p < 0.05$
Temperate steppe	y = 4.72x - 9273.51	0.54598	$p < 0.01$
Temperate desert-steppe	y = 2.05x - 4000.22	0.2783	$p < 0.05$
Temperate desert	y = 2.32x - 4555.05	0.38181	$p < 0.01$

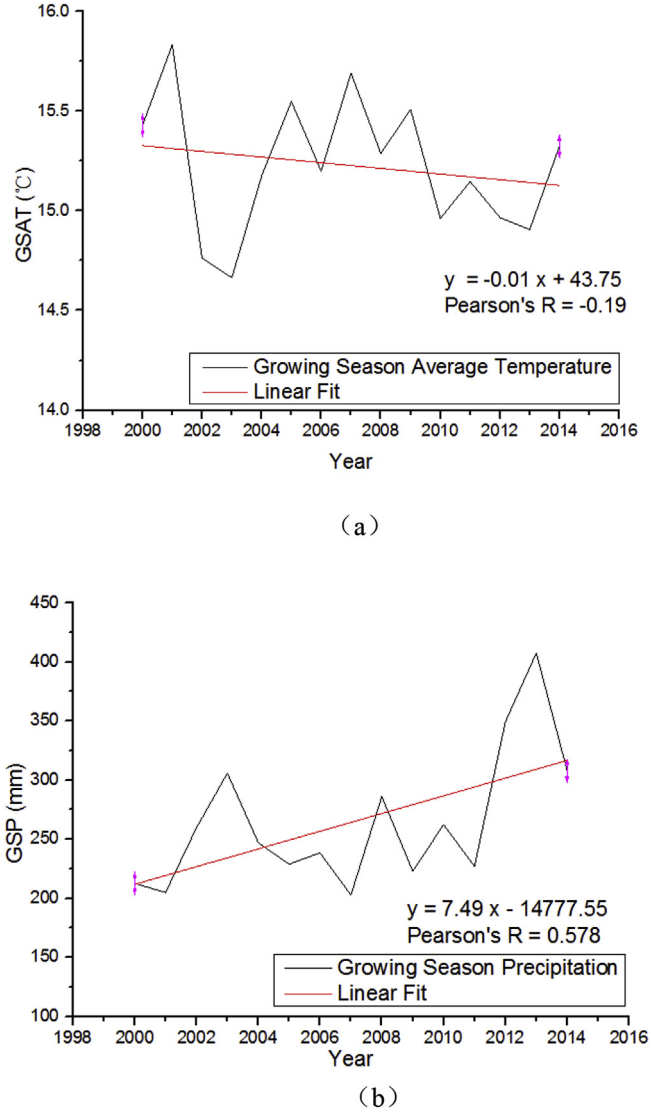


Fig. 8. Variations in GSAT (a) and GSP (b) in the study area, 2000–2014.

(Fig. 8a), which did not pass the significance level test; thus, the decrease rate was deemed insignificant. Equation (5) and Equation (6) are respectively used to calculate the partial correlation coefficients of NPP with GSAT and GSP. The partial correlation between NPP and GSAT is shown in Fig. 9; this correlation is not significant in the vast majority of the study area, with a negative correlation in 71.59% of the total area. A significant negative correlation is observed only in 0.31% of the study area, mainly in the middle and eastern regions of Xilin Gol League, the western regions of Chifeng, and the southwest regions of Erdos. A positive partial correlation is observed in 28.41% of the total area, with a significant positive partial correlation in 1.2% of that area, mainly in eastern regions of Ordos and northeast regions of Hulun Buir.

LST expresses the temperature status of the atmosphere–surface junction. The changes in LST affect the growth and development of vegetation by changing the material and energy balance between the surface and atmosphere and then affect the protection and evolution of the regional ecological environment (Li et al., 2014). LST and NPP data are also derived from MODIS data products, which have spatiotemporal consistency compared with the air temperature derived from meteorological stations. Therefore, Equation (5) was used in this paper to calculate the correlation between NPP and the GSALST of the study area (Fig. 10). Results show that there was a negative correlation between the grassland NPP and GSALST in 95.81% of the total grasslands in the study area. A significant negative correlation is observed in 65.93% of that area, mainly in the vast majority of the Hulun Buir grassland regions, the middle and eastern regions of Xilin Gol League, the northern regions of Chifeng, the northern regions of Tongliao, the middle and southern regions of Hinggan League, and part of Hohhot and Ulanqab. Only 4.19% of the grassland in the study area showed a positive correlation, with less than 0.3% having a significant positive correlation. These results show that, compared with GSAT, GSALST exerted a more significant influence on grassland NPP.

Analysis of the GSP data (Fig. 8b) showed that the GSP of the study area had a wavelike increase from 2000 to 2014, with an overall increase rate of 7.49 mm/a, which passed the significance level test ($p < 0.05$). The partial correlation between NPP and GSP is shown in Fig. 11, indicating that GSP had a positive partial correlation with the grassland NPP in the majority of the study area, accounting for 98.07% of the total area. The significant positive partial correlation and the extremely significant positive partial correlation are observed in 54.78% of the total grassland area, mainly in western regions of Hulun Buir, most of the regions of Xilin Gol League, Hinggan League, and Tongliao, the northern regions of Chifeng, and the eastern regions of Bayannur and Erdos. Further analysis in combination with Fig. 4 indicated that regions showing a significant positive partial correlation were in accordance with the regions with low NPP values, thereby confirming that the increase in precipitation is of great significance to the ecological restoration of the study area. A significant negative partial correlation between NPP and GSP was only observed in less than 0.1% of the grassland in the study area, and a negative (but not significant) partial correlation was observed in less than 2% of the total area, mainly in Xilin Gol League and a small part of Hulun Buir, the southern regions of Chifeng, the northern regions of Baotou, and the southwestern regions of Erdos.

In order to further distinguish the dominant role of GSP and GSAT on the grassland NPP change in the study area, the response of grassland NPP to climatic factors was divided into four categories: GSAT as the main influencing factor, GSP as the main influencing factor, GSP and GSAT together, and the remaining factors (Fig. 12). The statistical analysis results showed that the NPP of grassland in the study area was mainly affected by GSP, and only a small part of the area was affected by GSP and GSAT, which was mainly distributed in the northeast of Ordos.

To further analyze the correlation between NPP and climatic factors or GSALST across various types of grassland, the distribution of grassland types in the study area is used in this paper to conduct partition statistics (Fig. 13) on the partial correlation coefficients between NPP

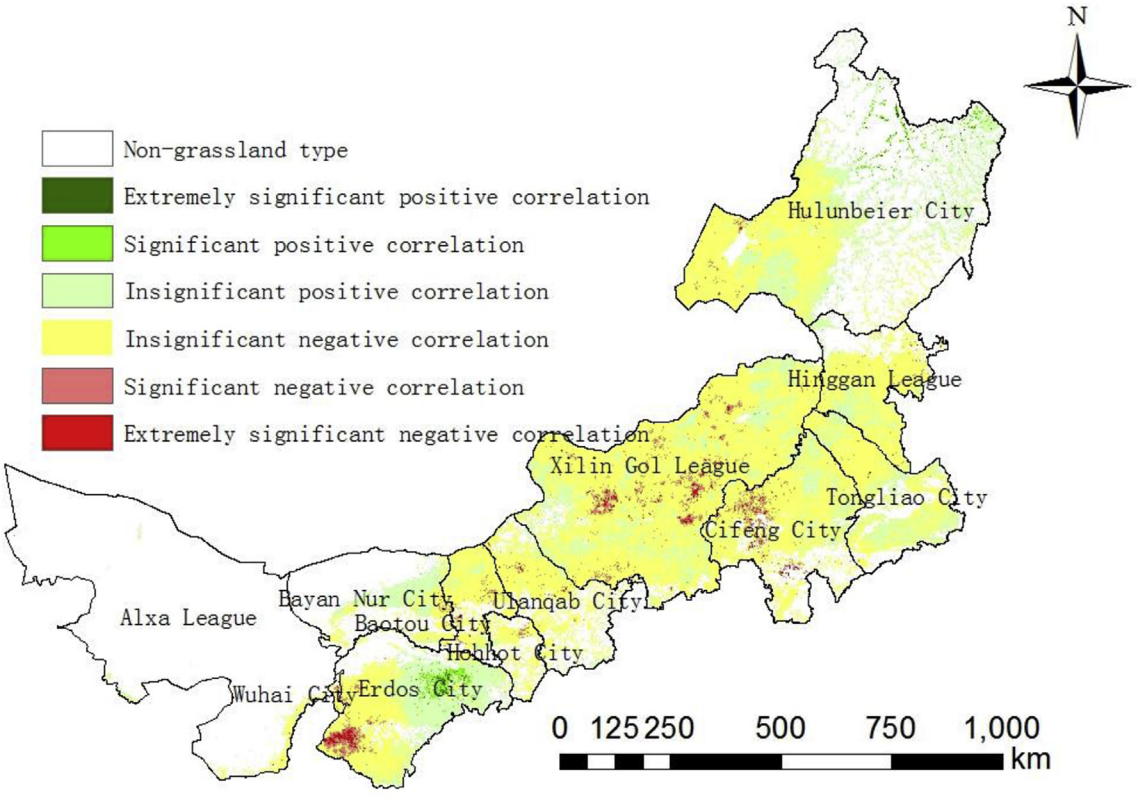


Fig. 9. Correlation between grassland NPP and GSAT in the study area.

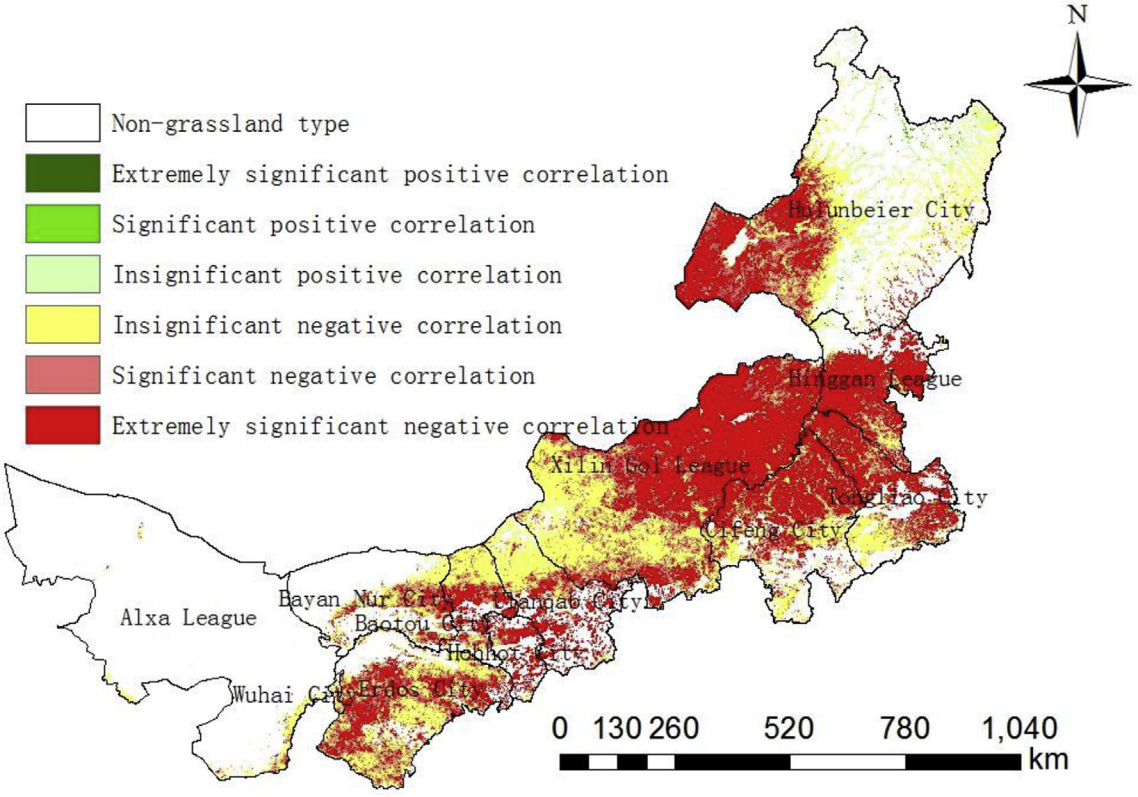


Fig. 10. Correlation between grassland NPP and GSALST in the study area.

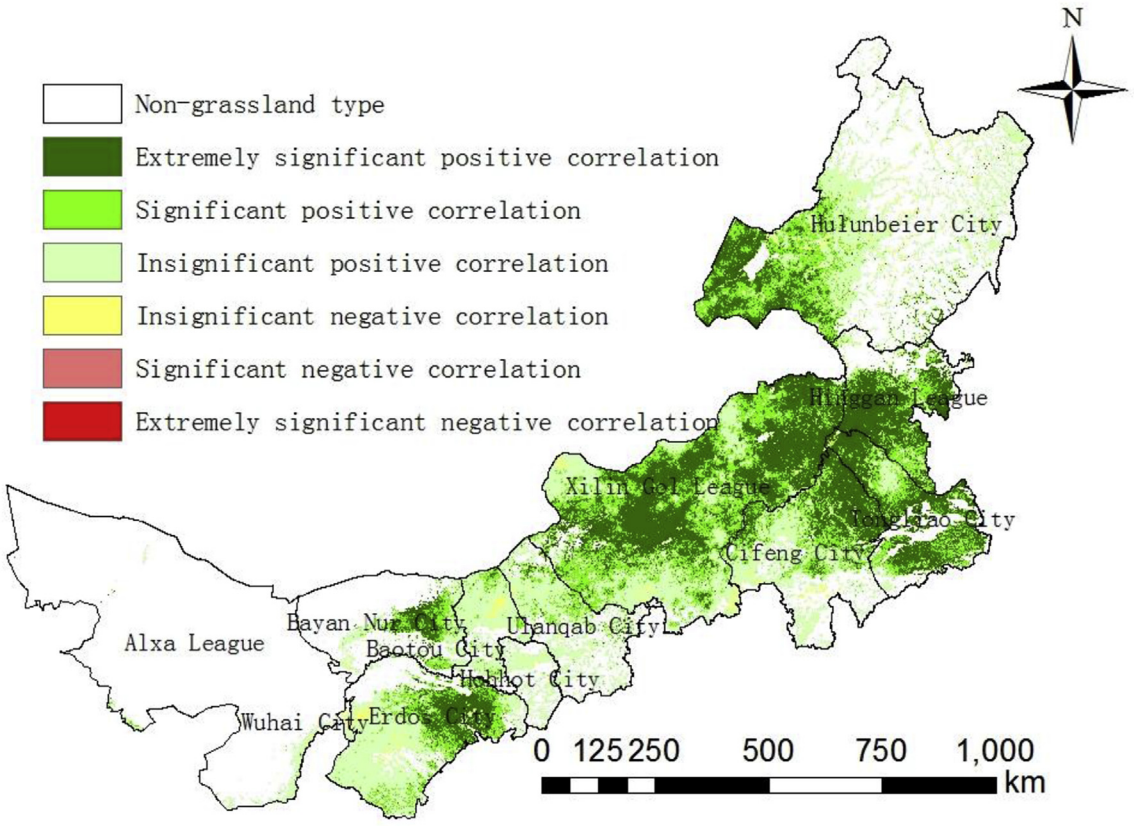


Fig. 11. Correlation between grassland NPP and GSP in the study area.

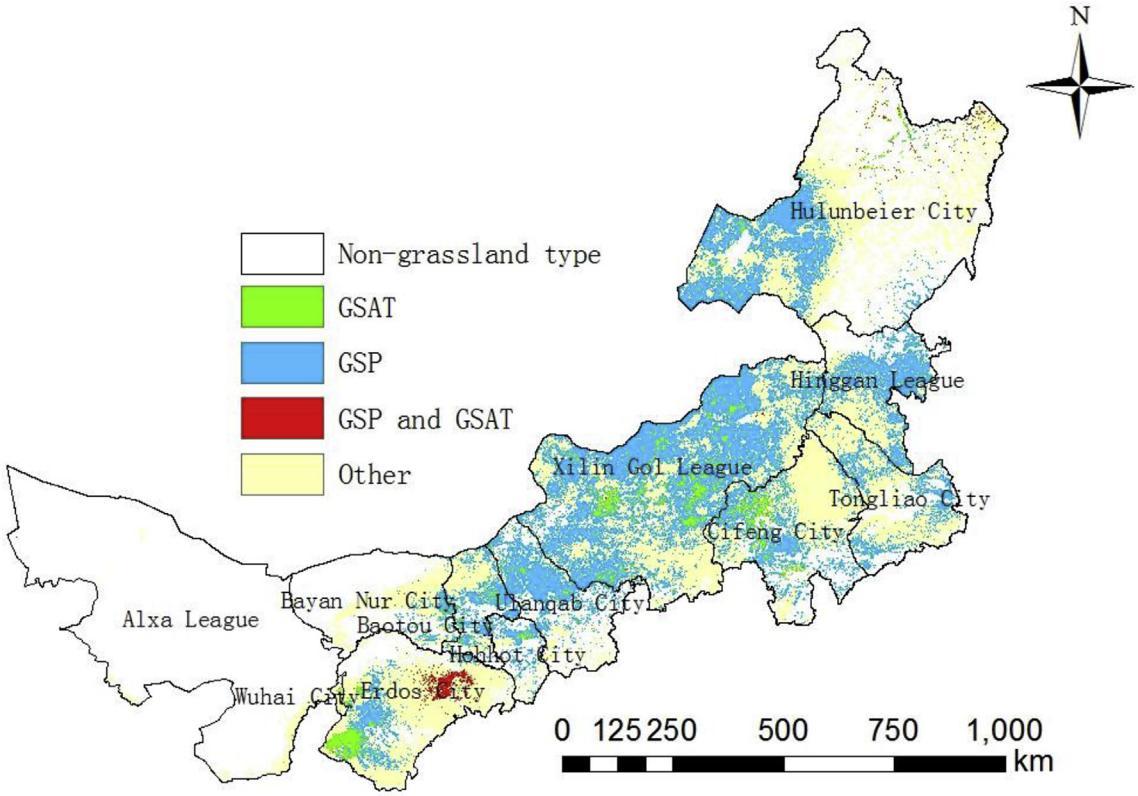
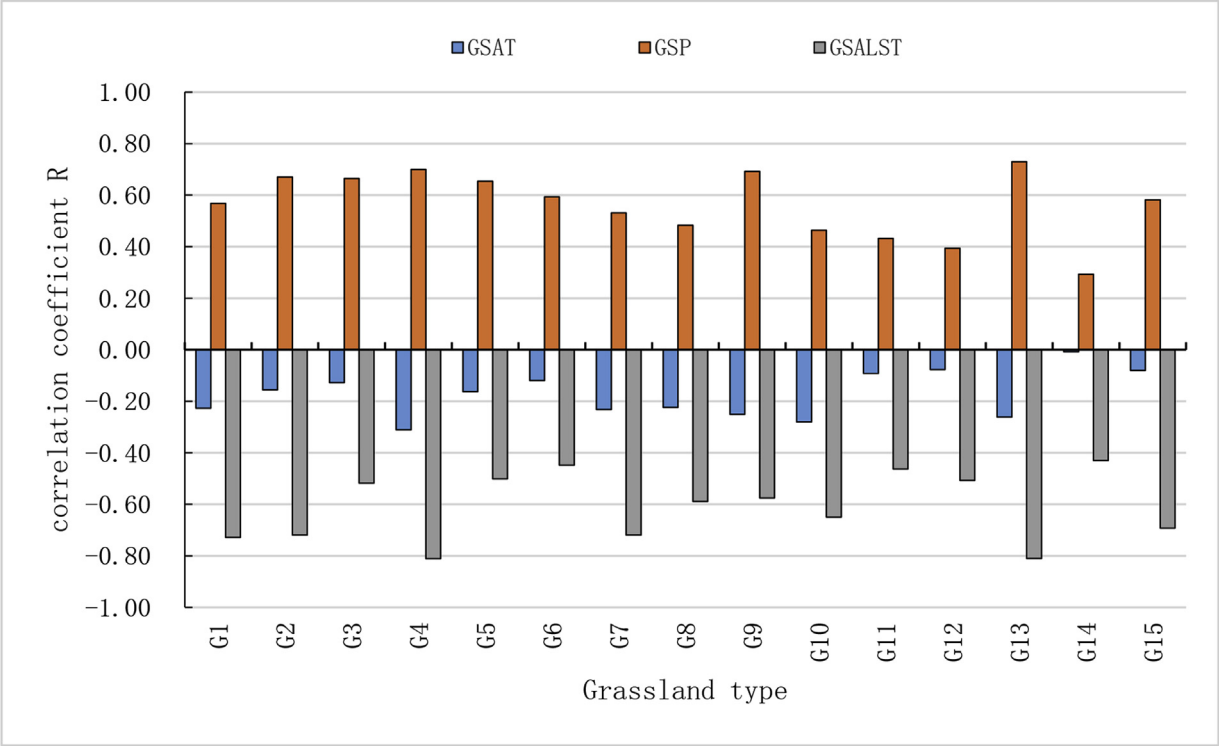


Fig. 12. Comprehensive analysis of climatic factors affecting the grassland NPP in the study area.



G1: Temperate meadow-steppe; G2: Temperate steppe; G3: Temperate desert-steppe;
G4: Alpine steppe; G5: Temperate steppe-desert; G6: Temperate desert;
G7: Warm tussock; G8: Warm shrub; G9: Tropical tussock;
G10: Tropical shrub; G11: Lowland saline meadow; G12: Temperate mountain meadow;
G13: Alpine meadow; G14: Marsh; G15: Improved grassland.

Fig. 13. Correlation coefficients between various grassland types and climatic factors/GSALST.

and GSAT/GSP, as well as the correlation coefficients between NPP and GSALST. On the whole, the partial correlations of different grassland types with climatic factors differ greatly to their correlations with GSALST. The partial correlations between NPP and GSP in different grassland types are all positive, while their correlations with GSAT and GSALST are all negative, and the partial correlations of different grassland types with GSAT and their correlations with GSALST are found to have very similar variation trends. Correlations between NPP and GSP in the 15 grassland types were all positive, with an average partial correlation coefficient of 0.6. Among them, the alpine meadows had the highest partial correlation coefficient of 0.73, and the marsh had the lowest partial correlation coefficient of 0.29. The average partial correlation coefficient between NPP and GSAT was −0.17, the alpine steppes had the highest partial correlation coefficient of −0.31, and the marsh grassland had the lowest partial correlation coefficient of −0.01. The average correlation coefficient between NPP and GSALST was −0.61; alpine steppes and alpine meadows had the highest correlation coefficient of −0.81, which is a significant negative correlation. The marsh had the lowest correlation coefficient of −0.43.

3.4. Influence of human activities on grassland NPP in inner Mongolia

Apart from climate, human activities are also important factors influencing the variations in grassland NPP in Inner Mongolia. The yearbook data of Inner Mongolia (CSY, 2015) demonstrate that the number of heavy livestock (cows, horses, camels, etc.) and sheep respectively increased by 25.85% (6.674 million to 8.399 million) and 50.42% (35.516–55.693 million) from the beginning of 2000 to the end of 2014. The increase in livestock was extremely unfavorable for the local ecological restoration and NPP increase, and NPP presented a trend of wavelike increase in the study area. The primary reason is that, since the beginning of the 21st century, China has implemented a series of ecological restoration projects, such as the Beijing-Tianjin Sandstorm Source Control (Gao et al., 2007; Shi et al., 2009), Green for Grain (Wang et al., 2015; Zhang et al., 2016), Returning Grazing Land to Grassland (Zhang et al., 2016), and the Enclosing-Transferring Strategy (Li et al., 2015), all of which have played a positive role in the environmental improvement and grassland vegetation restoration of ecologically vulnerable regions in Inner Mongolia. Based on this, we used the 2001–2015 Chinese Statistical Yearbooks (CSY, 2015)to create a diagram of the annual newly increased and cumulative area of fenced rangeland and planted grass in the study area (Fig. 14). Results show that the area of fenced rangeland in Inner Mongolia increased from $845.07 \times 10^4\,hm^2$ in 2000 to $3092.48 \times 10^4\,hm^2$ in 2014, and the cumulative planted grass area reached $1955.52 \times 10^4\,hm^2$ during the 15 years considered. The large-scale implementation of the Enclosing-Transferring Strategy, Green for Grain and Returning Grazing Land to Grassland projects have provided a “green basis” for the significant increase in grassland NPP.

In order to examine the influence of China's ecological restoration policies on grassland NPP in the study area, correlations between NPP and the cumulative newly increased fenced rangeland or planted grass

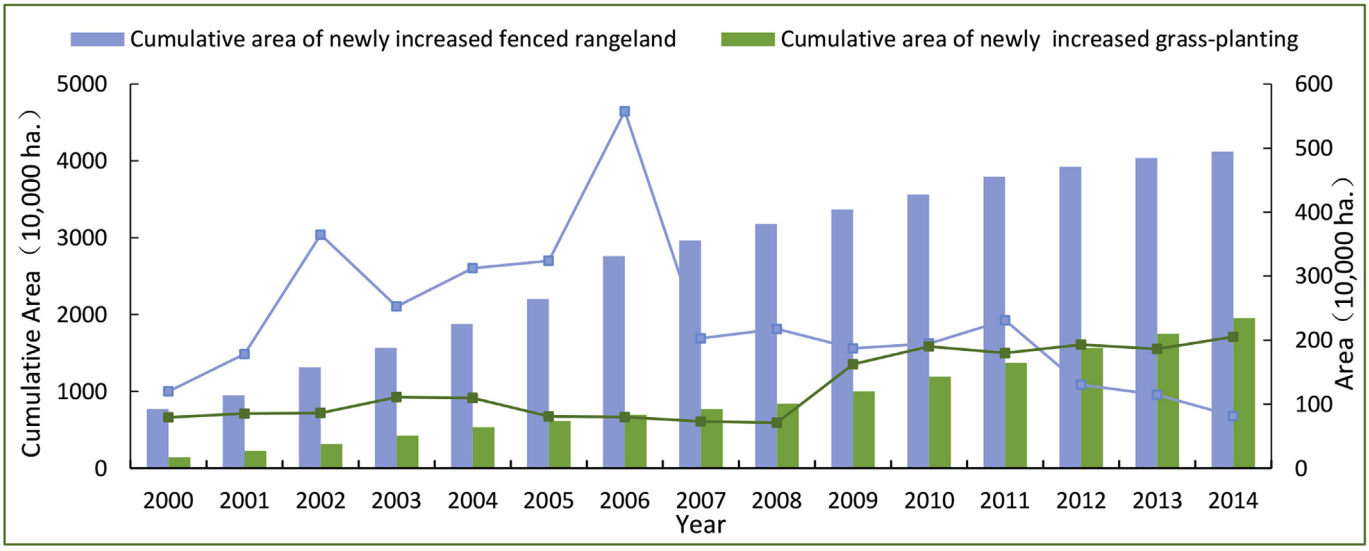


Fig. 14. Statistical chart of annual newly increased fenced rangeland and planted grass area.

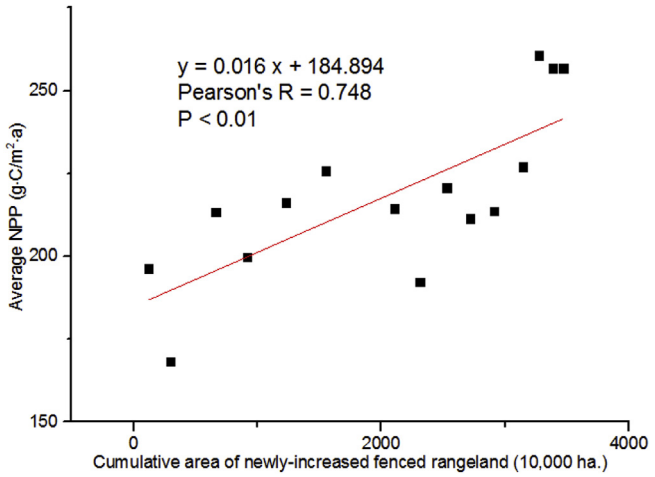


Fig. 15. NPP and the cumulative area of newly increased fenced rangeland.

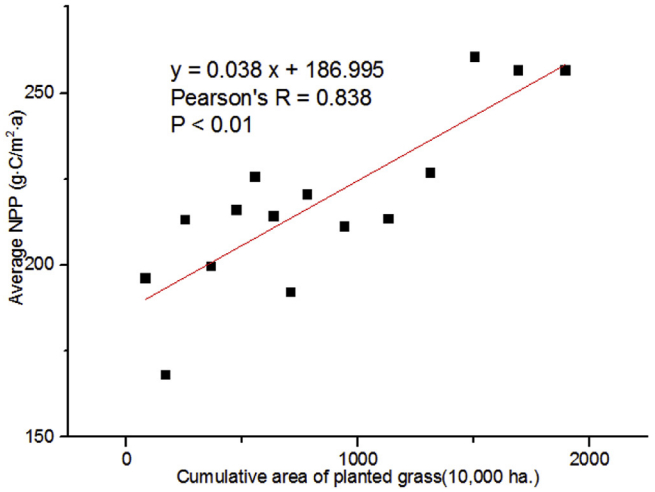


Fig. 16. NPP and the annual cumulative planted grass area.

area were analyzed in this paper (Fig. 15; Fig. 16). As can be seen in Fig. 15, the grassland NPP and the cumulative area of the newly increased fenced rangeland had a linear relationship, with a correlation coefficient of 0.748; Fig. 16 shows that the grassland NPP and the cumulative planted grass area also had a linear relationship, with a correlation coefficient of 0.838. Both results were extremely significantly correlated with the variations in NPP. Therefore, although the yearly increase in the number of human-raised livestock had a significantly negative influence on the increase in NPP, the related ecological protection and restoration policies provided important guarantees for the growth of grassland NPP in the study area.

4. Discussion

At present, there are many studies on the temporal and spatial evolution characteristics of grassland NPP in Inner Mongolia (Dai et al., 2016). Whether using MODIS17A3-NPP or NPP data based on CASA (Bao et al. (2016), CENTURY (Guo et al. (2016), or other estimation models (Zhang et al., 2011), the results are basically consistent with the conclusions of this paper; that is, the NPP of grassland in the study area has a fluctuating upward trend during the study period. Limited by MODIS data, the paper only analyzed the spatiotemporal evolution of grassland NPP in Inner Mongolia during 2000–2014. The grassland NPP and ecological restoration have obvious response mechanisms to human activities such as grass-planting, but the lag between grass-planting and ecological restoration and grassland productivity enhancement needs to be further studied in combination with longer time series analyses. Meanwhile, the time-lag response of grassland NPP to climate factors has attracted considerable attention and emerged as a hot topic in climate change studies (Wu et al., 2015; Zhou et al., 2015; Liang et al., 2015). Therefore, future studies will use NPP estimation models (such as the CASA model) combined with data from multiple sources (such as MODIS, NOAA, and SPOT-VGT) to estimate the grassland NPP in different time periods. The time-lag of the grassland NPP response to climate factors and the spatiotemporal variation characteristics of longer time series will also be further analyzed.

When analyzing the impacts of precipitation and temperature on grassland NPP, most studies suggest that the changes in grassland NPP in the study area are mainly affected by precipitation, especially in temperate desert steppes (Gerten et al., 2008; Pan et al., 2007), which is consistent with the conclusions of this paper. However, there are also some studies that suggest that grassland NPP in the study area is affected by both temperature and precipitation (Mu et al., 2017; Guo et al., 2016). The main reasons for the different conclusions may be due to the different time intervals of the analysis or the different NPP data sources used. In addition, the response of grassland NPP to climate

change and human activities is a complex process of much concern to researchers (Zhao et al., 2017). However, due to the diversity of human activities, it is difficult to quantitatively analyze the impact of certain human activities on grassland NPP (Miao et al., 2015). At the same time, the coexistence of climate factors and human activities makes it difficult to distinguish clearly which areas are dominated by human activities and which areas are dominated by climate factors. Subsequent studies will simulate grassland NPP based on climatic factors and compare it with actual grassland NPP to determine whether the dominant factor of grassland NPP change is human activity or climate factors.

5. Conclusions

In this study, we combined MOD17A3-NPP and LST products with climate factors to explore the spatiotemporal patterns in grassland NPP changes, as well as their driving forces, in Inner Mongolia from 2000 to 2014. The results showed that the grassland NPP in Inner Mongolia increased overall, with some fluctuations. In addition, it presented a trend of gradual increase from west to east and from south to north, with the distribution showing an evident longitudinal zonality. The annual grassland NPP presented a significant increase in 31.93% of the study area, and an extremely significant increase was observed in 13.36% of the area. Results indicated that the productivity has been steadily improving in Inner Mongolia. The partial correlation/correlation of NPP with GSAT, GSP, and GSALST was calculated by using a pixel-based linear trend method. It was found that GSAT has less influence on the change in NPP than does GSALST, but the NPP of grassland was highly dependent on GSP, especially in temperate meadow-steppes and temperate steppes in the middle and eastern part of Inner Mongolia. The statistical results of various grassland types clearly showed that NPP was positively correlated with GSP except temperate desert type, lowland saline meadow type and marsh type ($P < 0.05$), but negatively correlated with GSALST except warm shrub type, tropical shrub type, lowland saline meadow type, temperate mountain meadow type and marsh type ($P < 0.05$). In terms of anthropogenic activity, the statistical analyses demonstrated that the NPP of grassland during the study period has a high correlation with the cumulative area of fenced rangeland and the cumulative planted grass area, thereby suggesting that ecological restoration programs have been important for ecological recovery in Inner Mongolia in recent decades.

Author contributions

Yuling Zhao collected the data and drafted the paper, Haixin Liu and Anbing Zhang have been collected the data and conducted the laboratory analysis and reading the paper; Haixin Liu and Ximin Cui conceived the main idea of the paper, analyzed the data and wrote the draft. Anzhou Zhao helped with writing and editing the paper.

Declarations of interest

None.

Funding

This work was supported by grants from the Natural Science Foundation of Hebei Province of China (D2015402134; D2017402159; 15967663D), the Education Department, Hebei Province (BJ2018043 and ZD2018230), Handan Municipal Science and Technology Bureau (1723209055-2; 1721203048-2 and 1724230057-1), and Hebei Water Ecological Civilization and Social Governance Research Center (2018SZX14).

Acknowledgments

Appreciation is extended to Yichun Xie at Eastern Michigan University for the collection of relevant data and to the two anonymous reviewers for their valuable comments on the manuscript.

References

Bao, G., Bao, Y., Qin, Z., Xin, X., Bao, Y., Bayarsaikan, S., Zhou, Y., Chuntai, B., 2016. Modeling net primary productivity of terrestrial ecosystems in the semi-arid climate of the Mongolian plateau using lswi-based casa ecosystem model. Int.J.Appl.Earth.Obs. 46, 84–93.

Cramer, W., Kicklighter, D.W., Bondeau, A.M.B., Churkina, C., Nemry, B., 1999. Comparing global models of terrestrial net primary productivity (npp):overview and key results. Glob. Chang. Biol. 5 (S1), 46–55.

CSY, 2015. China Statistical Yearbook China Statistical Publishing House, Beijing 2001, 2002,2003,2004,2005,2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013.

Dai, E., Huang, Y., Zhuo, W.U., Zhao, D., 2016. Analysis of spatio-temporal features of a carbon source/sink and its relationship to climatic factors in the inner Mongolia grassland ecosystem. J. Geogr. Sci. 26 (3), 297–312.

Field, C.B., Randerson, J.T., Malmstroem, C.M., 1995. Global net primary production: combining ecology and remote sensing. Remote Sens. Environ. 51 (1), 74–88.

Foley, J.A., 1994. Net primary productivity in the terrestrial biosphere: the application of a global model. J. Geophys. Res.: Atmosphere 99 (D10), 20773–20783.

Gao, X., Bai, Y., Xu, Q., 2007. Implementation progress of Shanxi grassland construction of wind and sand control project in Beijing and Tianjin region. Pratacult. Sci. 24 (11), 11–13.

Gerten, D., Luo, Y., Maire, G.L., Parton, W.J., Keough, C., Weng, E., et al., 2008. Modelled effects of precipitation on ecosystem carbon and water dynamics in different climatic zones. Global change Biol 14 (10), 2365–2379.

Guo, L., Hao, C., Shaohong, W.U., Zhao, D., Gao, J., 2016. Analysis of changes in net primary productivity and its susceptibility to climate change of inner Mongolian grasslands using the century model. Geogr. Res. 35 (2), 271–284.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. P. Natl. Acad. Sci. USA 104 (31), 12942–12947.

Han, F., Zhang, Q., Buyantuev, A., Niu, J., Liu, P., Li, X., Kang, S., Zhang, J., Chang, C., Li, Y., 2015. Effects of climate change on phenology and primary productivity in the desert steppe of Inner Mongolia. J. Arid Land 7 (2), 251–263.

Imhoff, M.L., Bounoua, L., DeFries, R., Lawrence, W.T., Stutzer, D., Tucker, C.J., Ricketts, T., 2004. The consequences of urban land transformation on net primary productivity in the United States. Remote Sens. Environ. 89 (4), 434–443.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123 (1), 1–22.

Li, H., Sun, D., Yu, Y., Wang, H., Liu, Y., Liu, Q., Du, Y., Wang, H., Cao, B., 2014. Evaluation of the viirs and modis lst products in an arid area of northwest China. Remote Sens. Environ. 142 (1), 111–121.

Li, S., Xie*, Y., Brown, D.G., Bai, B., Jinhua, J., Judd, K., 2013. Spatial variability of the adaptation of grassland vegetation to climatic change in Inner Mongolia of China. Appl. Geogr. 43, 1–12. https://doi.org/10.1016/j.apgeog.2013.05.008.

Li, Y., Yan, Z., Guo, D., Wang, H., Su, S., Li, X., Fu, H., 2015. Effects of fencing and grazing on vegetation and soil physical and chemical properties in an alpine meadow in the Qinghai Lake Basin. Acta Pratacult. Siniva 24 (10), 33–39.

Liang, W., Yang, Y., Fan, D., Guan, H., Zhang, T., Long, D., 2015. Analysis of spatial and temporal patterns of net primary production and their climate controls in China from 1982 to 2010. Agric. For. Meteorol. 204, 22–36.

Lin, C., Dugarsuren, N., 2015. Deriving the spatiotemporal NPP pattern in terrestrial ecosystems of Mongolia using MODIS imagery. Photogramm. Eng. Rem. Sens. 81 (7), 587–598.

Long, H., Xiaobing, L.I., Hong, W., Wei, D., 2010. Net primary productivity (npp) of grassland ecosystem and its relationship with climate in inner Mongolia. Acta Ecol. Sin. 34 (7), 781–791.

Miao, L., Jiang, C., Xue, B., Liu, Q., He, B., Nath, R., et al., 2015. Vegetation dynamics and factor analysis in arid and semi-arid inner Mongolia. Environ. Earth. SCI. 73 (5), 2343–2352.

Mowll, W., Blumenthal, D.M., Cherwin, K., Smith, A., Symstad, A.J., Vermeire, L.T., et al., 2015. Climatic controls of aboveground net primary production in semi-arid grasslands along a latitudinal gradient portend low sensitivity to warming. Oecologia 177 (4), 959–969.

Mu, S.J., Li, J.L., Yang, H.F., GANG, C.C., CHEN, Y.Z., 2013. Spatio-temporal variation analysis of grassland net primary productivity and its relationship with climate over the past 10 years in Inner Mongolia. Acta Pratacult. Siniva 22 (3), 6–15.

Mu, S., You, Y., Zhu, C., Zhou, K., 2017. Spatio-temporal patterns of precipitation-use efficiency of grassland in Northwestern China. Acta Ecol. Sin. 37 (05), 1458–1471.

Pan, M., Liang, J., Jia, L., et al., 2007. Temporal and spatial pattern of temperate steppe NPP in inner Mongolia. J. Northwest For. Univ. (6), 233–240.

Sha, Z., Bai, Y., Xie*, Y., Yu, M., Zhang, L., 2009. Using a hybrid fuzzy classifier (HFC) to map typical grassland vegetation in Xilin River Basin, Inner Mongolia, China. International INT. J. REMOTE. SENS. 29 (8), 2317–2337.

Shi, S., Zou, X., Zhang, C., Su, G., 2009. Investigation of vegetation restoration in the area of beijing and tianjin sandstorm source control project. Science of Soil & Water Conservation 7 (2), 86–92.

Steffen, W., Noble, I., Canadell, J., Apps, M., Schulze, E.D., Jarvis, P.G., 1998. The terrestrial carbon cycle: implications for the kyoto protocol. Sci 280 (5368), 1393.
Sun, G.N., Wang, M.H., 2008. Study on relation and distribution between vegetative coverage and land degradation in inner Mongolia. J. Arid Land Resour. Environ. 22 (2), 140–144.
Wang, F., An, P., Cai, L., Huang, X., Hao, J., 2015. Monitoring effects of ecosystem restructuring project for returning grain plots to forestry in Wuchuan county of Inner Mongolia based on RS and GIS. Transactions of the CSAE 31 (11), 269–277.
Wu, D., Zhao, X., Liang, S., Zhou, T., Huang, K., Tang, B., 2015. Time-lag effects of global vegetation responses to climate change. Glob. Chang. Biol. 21 (9), 3520.
Xia, L., Wang, F., Mu, X., Jin, K., Sun, W., Gao, P., Zhao, G., 2015. Water use efficiency of net primary production in global terrestrial ecosystems. J. Earth Syst. Sci. 124 (5), 921–931.
Xie, Y., Zhang, Y., Lan, H., Mao, L., Jin, H., Zeng, S., 2018. Investigating long-term trends of climate change and their spatial variations caused by regional and local environments through data mining. J. Geogr. Sci. 28 (6), 802–818.
Yuan, F., Wu, J., Li, A., Rowe, H., Bai, Y., Huang, J., Han, X., 2015. Spatial patterns of soil nutrients, plant diversity, and aboveground biomass in the Inner Mongolia grassland: before and after a biodiversity removal experiment. Landsc. Ecol. Eng. 30 (9), 1737–1750.
Zhang, G., Kang, Y., Han, G., Sakurai, K., 2011. Effect of climate change over the past half century on the distribution, extent and NPP of ecosystems of Inner Mongolia. Glob. Chang. Biol. 17 (1), 377–389.
Zhang, H.Y., Fan, J.W., Shao, Q.Q., 2016. Ecosystem dynamics in the "returning rangeland to grassland" programs. Acta Pratacult. Siniva 25 (4), 1–15.
Zhang, M., Lal, R., Zhao, Y., Jiang, W., Chen, Q., 2017a. Spatial and temporal variability in the net primary production of grassland in China and its relation to climate factors. Plant Ecol. 218 (9), 1117–1133.
Zhang, R., Zhou, Y., Luo, H., Wang, F., Wang, S., 2017b. Estimation and analysis of spatiotemporal dynamics of the net primary productivity integrating efficiency model with process model in karst area. Remote Sens-basel. 9 (5), 477.
Zhao, A., Zhang, A., Lu, C., Wang, D., Wang, H., Liu, H., 2017. Spatiotemporal variation of vegetation coverage before and after implementation of grain for green program in loess plateau, China. Ecol. Eng. 104, 13–22.
Zhao, M., Heinsch, F.A., Nemani, R.R., Running, S.W., 2005. Improvements of the MODIS terrestrial gross and net primary production global data set. Remote Sens. Environ. 95 (2), 164–176.
Zhou, Y., Zhang, L., Fensholt, R., Wang, K., Vitkovskaya, I., Tian, F., 2015. Climate contributions to vegetation variations in central asian drylands: pre- and post-USSR collapse. Remote Sens-basel 7 (3), 2449–2470.
Zhu, W., Chen, Y., Xu, D., LI, J., 2005. Advances in terrestrial net primary productivity (NPP) estimation models. Chin. J. Ecol. 24 (3), 296–300.